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PERFORMANCE OF AQUEOUS FILM FORMING FOAM (AFFF) ON LARGE-SCALE HYDROPROCESSED RENEWABLE JET (HRJ) FUEL FIRES

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14. ABSTRACT

Bio-oil derived hydroprocessed renewable jet (HRJ) fuel blended with JP-8 is being evaluated for use in United States Air Force (USAF) aircraft and support equipment and vehicles. The fire protection safety risk to the first responder associated with this fuel must be established. This program was designed to determine if Military Specification MIL-F-24385F Aqueous Film Forming Foam (AFFF) has the capability of extinguishing large scale HRJ/JP-8 blended fuel fires. The assessment included quantity of agent required for extinguishment of 465 m^2 (5,000 ft^2) using standard pressure and ultra high pressure delivered from a modified P-19 fire truck. The extinguishment characteristics of HRJ blend fuel fires were compared with fires using pure JP-8 fuel. Heat flux and ambient air temperature adjacent to the fire pit were also measured.

15. SUBJECT TERMS
hydroprocessed renewable jet fuel, HRJ, fire suppression, AFFF, alternative fuel, JP-8

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. SUMMARY

The Air Force's reliance on foreign petroleum sources has been recognized as a major vulnerability to the national defense. As a result, a goal of supplying 50 percent of the Air Force fuel from alternative sources by 2016 has been established. Bio-oil derived hydroprocessed renewable jet fuels (HRJ)), are alternative fuels that are being evaluated for use in United States Air Force (USAF) aircraft, support equipment and vehicles (SE&V). Blending HRJ with JP-8 could significantly reduce dependence on petroleum oil sources and thereby improve national security.

With the increased interest in alternative fuels, there are questions of whether existing aqueous film forming foam (AFFF) firefighting agents and equipment are capable of extinguishing alternative fuel fires or if firefighters will need additional or new tools to successfully extinguish these fires. Testing was performed at the request of the Aeronautical Systems Center Alternative Fuels Certification Division (ASC/WNN).

This test series included extinguishment of 15 fires, nine using JP-8 and six using HRJ/JP-8 blend. Approximately half of each group was extinguished using UHP and the remaining using standard pressure foam/water agent application. Measurements of extinguishment time, agent usage and application rates were obtained. Heat flux and air temperature measurements in the vicinity of the fire were also obtained for comparison of local heating from the two fuels.

- The HRJ/JP-8 blend fuel was extinguished effectively with existing AFFF solution using standard pressure and UHP.
- Large scale fire suppression results mirrored small scale results: AFFF is equally effective on JP-8 and HRJ/JP-8 blend fuel.
- Radiant heat flux measurements were inconclusive due to wind effects.

In conclusion, modifications to the firefighting equipment and solutions are not required for extinguishment of fires involving a 50 percent blend of JP-8 and HRJ fuel for either standard pressure or UHP.

2. INTRODUCTION

2.1. Background

The Air Force's reliance on foreign petroleum sources has been recognized as a major vulnerability to the national defense. As a result, a goal of supplying 50 percent of the Air Force fuel from alternative sources by 2016 has been established. Bio-oil derived HRJ, also known as HEFA, fuels are alternative fuels that are being evaluated for use in USAF aircraft SE&V. In support of this objective, the Air Force purchased HRJ fuel based on camelina seed oil, tallow, and animal fats and oil feedstocks blended with JP-8 [1] to support certification efforts. Camelina oil seed is nonfood source grain that can be used for crop rotation in wheat fields. Blending HRJ with JP-8 could significantly reduce dependence on petroleum oil sources and thereby improve national security. The service has tested and certified HRJ as a 50 percent blend with regular jet fuel in the A-10 Thunderbolt II, the F-15 Eagle, the C-17 Globemaster III and the F-22 [2].

As with any new weapons system or other type of potential fire threat, the fire protection safety risk to the first responder must be established. With the increased interest in alternative fuels, there are questions of whether existing AFFF firefighting agents and equipment are capable of extinguishing alternative fuel fires or if firefighters will need additional or new tools to successfully extinguish these fires. Testing was performed at the request of the ASC/WNN.

Recent developments in UHP firefighting have shown significant reduction in agent usage when operating at up to 1.03 MPa (1500 psi) [3]. The new P-34 Rapid intervention vehicle uses this technology. Conventional fire trucks are typically equipped with firefighting systems operating at standard pressure between 689 kPa and 1722 kPa (100 and 250 psi). Performance of UHP-based firefighting systems on alternative fuel fires is of interest as well because these systems are becoming more ubiquitous in USAF inventory.

2.2. Objective

The objective was to determine if the effectiveness of existing large scale firefighting equipment using AFFF solutions were preserved when extinguishing fires with this blended fuel. This was evaluated using UHP and standard pressure firefighting systems. In addition, a comparison of radiant heating effects and temperature rise in the area surrounding the fires using these two fuels was to be evaluated.

2.3. Scope

This test series included extinguishment of 15 fires, nine using JP-8 and six using HRJ/JP-8 blend. Approximately half of each group was extinguished using UHP and the remaining using standard pressure foam/water agent application. Measurements of extinguishment time, agent usage and application rates were obtained. Heat flux and air temperature measurements in the vicinity of the fire were also obtained for comparison of local heating from the two fuels.

3. METHODS AND PROCEDURES

This test series consisted of a series of pool fires conducted in the south fire pit at the AFRL Test Range I facility, Tyndall AFB, FL. The planned tests consisted of a designed experiment including three replicates of a two factor, two level experiment (Table 1), comparing the firefighting performance of standard pressure and UHP extinguishing systems on fires of HRJ/JP-8 blended fuel and of JP-8.

Table 1. Text Matrix

	JP-8	HRJ Blend
Low Pressure	3	3
UHP	3	3

The intent of this experiment was to minimize variables other than the fuel type and agent discharge pressure. The same firefighter, nearly the same solution flow rate and the same truck were used for all tests in an effort to minimize variables. The standard pressure tests were conducted using normal 3% AFFF solution concentration, while the UHP tests used 6% concentration. Early in the development of UHP, 6% concentration had been established as the standard solution concentration. The 6% concentration was the result of using double the quantity of concentrate intended to be mixed at 3%. No concentrate intended to be used at 6% was used.

These tests were conducted using the Centrifugal UHP P-19 fire truck. This truck (**Error! Reference source not found.**) received extensive modifications during a prior program including the installation a18.9 L/s (300 gal/min) turret that provided either UHP at 8.3 mPa (1200 psi) or compressed air foam (CAF) at approximately 862 kPa (125 psi). This truck was equipped with a six-stage centrifugal pump capable of producing the UHP foam stream. CAF is obtained by providing a standard pressure foam stream, combined with a compressed air stream obtained from an engine mounted compressor. This truck also has a proportional control turret installed. This provides the firefighter the capability to control the turret movement at various speeds. The proportional control functioned with the UHP system and the CAF system. A complete description of the modifications to this truck and the testing program conducted is provided in the test report on that activity [4].

A standard pressure firefighting stream was obtained by replacing the UHP P-19 CAF nozzle with an Elkhart Brass, Inc. 5000-24E nozzle equipped with a 15.8 L/s (250 gal/min) stem. The air compressor was disabled resulting in a standard pressure firefighting stream of approximately 17.7 L/s (280 gal/min) at 1.17 MPa (170 psi).

An updated UHP nozzle was also obtained from Elkhart Brass Inc. This nozzle provided approximately15.8 L/s (250 gal/min) at 8.8 MPa (1280 psi). This flow is somewhat lower than the values obtained during previous testing of this truck (18.9 L/min or 300 gal/min) using the original nozzle due to a slight error in adjustment of the nozzle stem. This was judged to be acceptable for this test.

Figure 1. The Centrifugal Ultra High Pressure P-19

A nearly circular steel ring, 6 in tall, was installed in the AFRL Test Range I fire pit to limit the fire size to 465 m^2 (5,000 ft^2). Ring area measurements and computations are provided in Appendix B. Radiometers and thermocouples were installed adjacent to the fire ring to compare area heating obtained from each fuel. Agent extinguishment quantities were measured using elevation measurements of the premixed agent in the water tank.

The fire pit was filled with 25–51 mm (1–2 in) of water followed by 2,500 L (660 gal) of fuel for UHP fires and 2,880 L (760 gal) of fuel for standard pressure fires. This difference was based upon known fuel burning rate (4.4 mm/min) [8] and previous measurements of extinguishment times using UHP and standard pressure fire suppression. The additional 380 L (100 gal) of fuel was included for the standard pressure fires to assure that the fire didn't diminish as a result of fuel depletion that would occur due to longer extinguishment times.

Two radiometers and two thermocouples were installed adjacent to the fire ring to evaluate temperature and heat flux in the area near the fire. Radiometers were Medtherm model 64-25-20. Water cooling was provided during the tests. Calibration sheets are provided in Appendix A. The thermocouples were 1.59 mm (0.0625 in) diameter stainless steel sheathed, ungrounded, K type. The response time constant for these thermocouples is 6 s. Data was collected at one-second intervals and recorded using National Instruments Labview software shown in Appendix C.

All tests were conducted with steady wind less than 8 mi/h and gusts less than 10 mi/h. There were no additional environmental restrictions.

The fire truck was placed upwind from the fire, and the radiometers and thermocouples were placed in the approximate crosswind and downwind locations (Figure 2). They were mounted on an insulated pipe approximately 0.9 m (3 ft) above ground level (Figure 3). The thermocouples were placed behind the support pipe to assure that the air temperature measurement was not distorted by radiant heat transfer between the thermocouple and the fire.

Radiometer and thermocouple data were collected during the first 10 seconds of a 15-second pre-burn period. The pre-burn period was started once the ring area was fully involved in fire.

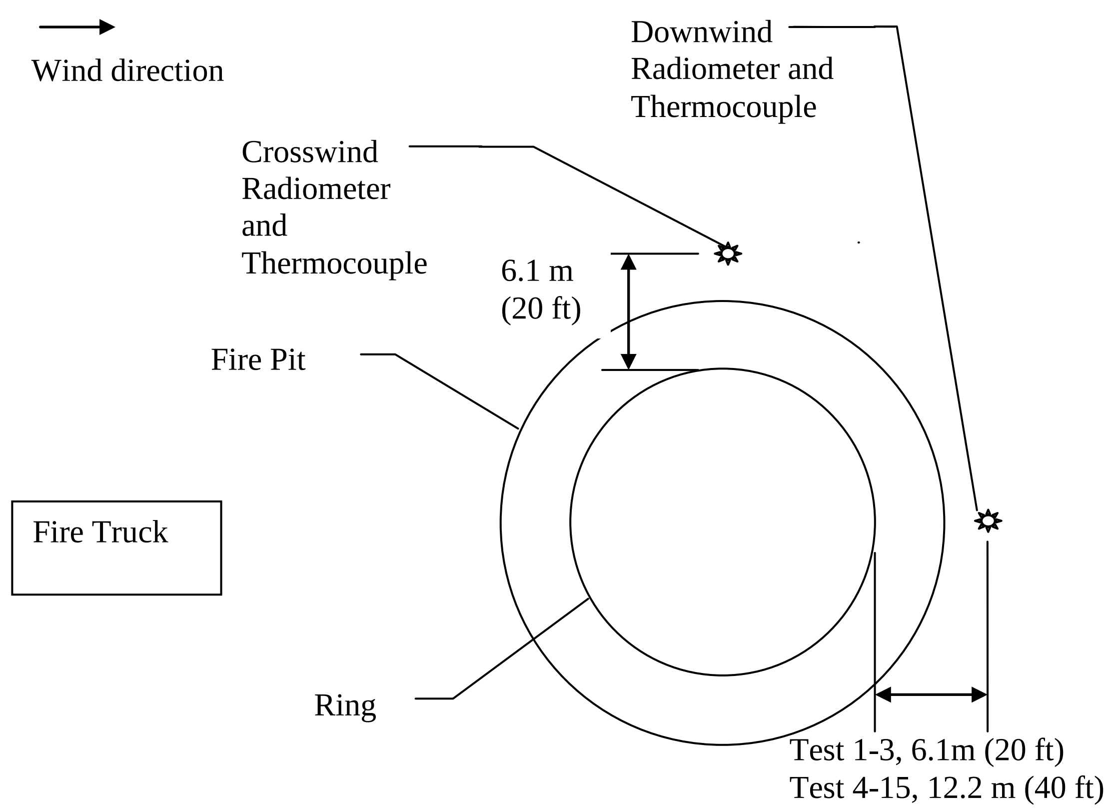

Figure 2. Fire Pit Arrangement

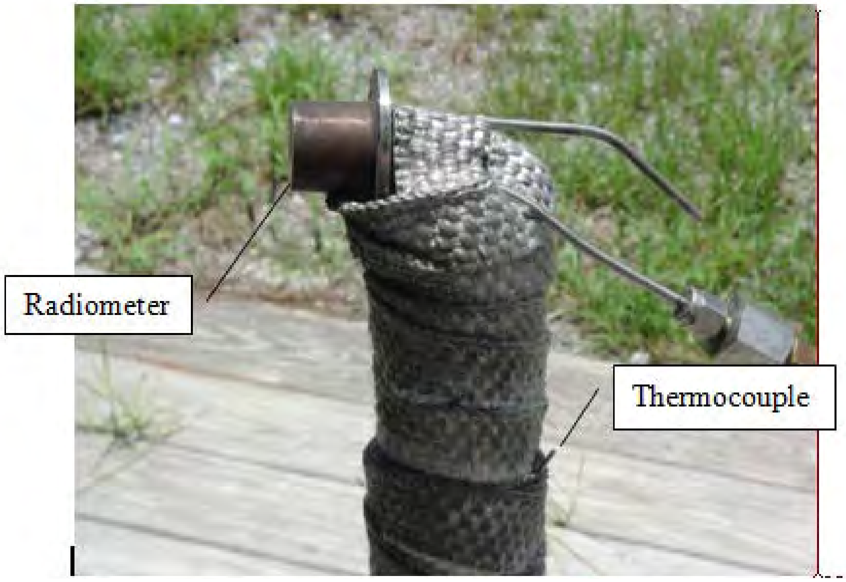

Figure 3. Radiometer and Thermocouple Installation

A manometer connected to the water tank was installed on the side of the fire truck for solution elevation measurement (Figure 4). This measurement was used in conjunction with a stopwatch to determine flow rate. The water volume in the tank was calibrated as a function of solution elevation by pumping increments of 90.9 kg (200 lb) of water out of the tank and noting the resultant water elevation. The water weight was measured using a platform scale. Calibration data is available in Appendix A. Solution elevation measurements were taken before and after conducting the fire tests on a level paved slab adjacent to the fire pit.

Water/AFFF solutions were premixed in the water tank to ensure consistent and repeatable AFFF concentration. Water levels were replenished after each test to ensure sufficient solution was available for fire extinguishment. Water levels were measured using the manometer and corresponding quantities of AFFF concentrate were added to the water tank. The truck was then driven to provide mixing of the AFFF concentrate and water.

Figure 4. Manometer for Tank Level Measurement

4. RESULTS AND DISCUSSION

Fifteen tests were conducted (Table 2) in a pseudo-random fashion. Two practice fires were conducted to familiarize the firefighter with the equipment and procedures. The first nine tests were conducted using JP-8, while the final six used the HRJ/JP-8 blended fuel. UHP and standard pressure tests were mixed randomly within these groups. Ideally, the fuel type test sequence would be random also, but the fuel tests were segregated because a limited quantity of HRJ blend fuel was available, and in order to conduct the fuel tests randomly, the fuel lines would have to be flushed following each change of fuel type, wasting approximately 60 gal of fuel for each change. In order to eliminate this waste of fuel, the tests were conducted with the fuel types separated sequentially.

Table 2. Test Summary

Test Number	Fuel	Pressure	Comments
1	JP-8	UHP	Practice fire
2	JP-8	UHP	Practice fire
3	JP-8	Standard	
4	JP-8	UHP	Invalid test
5	JP-8	Standard	
6	JP-8	Standard	Invalid test
7	JP-8	Standard	
8	JP-8	UHP	
9	JP-8	UHP	
10	HRJ/JP-8 Blend	UHP	No temperature and heat flux data
11	HRJ/JP-8 Blend	Standard	
12	HRJ/JP-8 Blend	Standard	
13	HRJ/JP-8 Blend	UHP	
14	HRJ/JP-8 Blend	Standard	
15	HRJ/JP-8 Blend	UHP	

The ring in the fire pit was initially set up as a 24.4 m (80-ft) diameter circle, resulting in a 467 m^2 (5030 ft^2) fire. The uncertainty of the area measurement (A) was estimated as 5% (Appendix D). This is primarily due to deviations from a circular ring, though the shape of the ring was corrected after each fire.

Agent quantity usage was measured using a linear least squares curve fit to the tank calibration data, providing a slope of 8.05 L/mm (29.54 gal/in) of tank elevation. The agent extinguishment quantity (Q) was determined by:

$$\boldsymbol{Q(L) = \frac{8.05 * (H2 - H1) * t}{t2}}$$

$$\boldsymbol{Q(gal) = \frac{29.54 * (H2 - H1) * t}{t2}}$$

Where *H2* and *H1* are the pretest and post test tank elevations in mm (in), *t* is the extinguishment time, and *t2* is the total time of agent discharge. Discharge and extinguishment times were determined by review of videos recorded during the fire. Agent quantity uncertainty was estimated at 5.2%, based on time measurement to the nearest second and height measurements to the nearest 0.8 mm (1/32 in).

The agent application rate was determined by:

$$Agent\ Application\ Rate = \frac{Q}{A}$$

The uncertainty of Agent Application Rate was estimated at 7.2% (Appendix D).

The measured agent application rates (Table 3) show lower average application rates were required for extinguishment of HRJ/JP-8 blend fires than JP-8 fires using standard pressure. Using UHP, the application rates were the same for both fuel types. The HRJ/JP-8 blend was extinguished with less agent than the JP-8 fires using standard pressure. A t-test was applied to the data for standard pressure application rates, indicating a difference between the two populations at a 97.4% confidence level assuming unpaired data with unequal variance and two tails [5]. The Student's t-test for the UHP fires indicated that there was no difference between the application rates for the JP-8 and HRJ/JP-8 blend fires.

Table 3. Agent Application Rates

	Standard Pressure		UHP	
	Test Number	Application Rate L/m^2 (gal/ft^2)	Test Number	Application Rate L/m^2 (gal/ft^2)
JP-8	3	1.26 (0.031)	8	.702 (0.017)
	5	1.29 (0.032)	9	.673 (0.017)
	7	1.25 (0.031)		
	Average	1.27 (0.031)	Average	.688 (0.017)
HRJ Blend	11	1.09 (0.027)	10	.694 (0.017)
	12	1.03 (0.025)	13	.616 (0.015)
	14	.944 (0.023)	15	.780 (0.019)
	Average	1.02 (0.025)	Average	.697 (0.017)

The thermal data from the downwind and crosswind radiometers and thermocouples are provided by showing average and maximum values measured during the pre-burn period (Table 4). Temperature data is provided as a temperature rise, which was computed by subtracting the

temperature measured just prior to lighting the fuel from the average and maximum values measured during the pre-burn data collection period.

Table 4. Crosswind and Downwind Thermal Data

		Heat Flux kW/m^2 (Btu/ft^2)				Temperature Rise °C (°F)			
		Average		Maximum		Average		Maximum	
Fuel	Test Number	Cross-wind	Down-wind	Cross-wind	Down-wind	Cross-wind	Down-wind	Cross-wind	Down-wind
JP-8	1	5.87 (1860)	8.06 (2550)	21.70 (6880)	26.60[1] (8430)	2.9 (5.2)	7.4 (13.3)	28.9 (52.1)	54.4[1] (97.9)
JP-8	2	3.67 (1160)	3.38 (1070)	3.99 (1260)	3.99[1] (1260)	0.3 (0.6)	4.6 (8.2)	0.9 (0.7)	4.7[1] (8.5)
JP-8	3	8.51 (2700)	8.41 (2670)	10.80 (3420)	16.60[1] 5260	0.3 (0.5)	9.1 (16.4)	0.3 (0.6)	15.1[1] (27.1)
JP-8	4	9.89 (3140)	13.37 (4240)	11.10 (3520)	15.90 (5040)	2.9 (5.2)	-4.3 (-7.8)	3.3 (6.0)	3.9 (-7.1)
JP-8	5	9.95 (3150)	30.21 (9580)	13.50 (4280)	40.10 12700	0.2 (0.4)	2.9 (5.2)	2.6 (4.6)	5.1 (9.2)
JP-8	6	Invalid test							
JP-8	7	8.31 (2630)	19.17 (6080)	9.38 (2970)	32.00 (10100)	0.9 (1.7)	7.9 (14.3)	1.4 (2.6)	9.3 (16.7)
JP-8	8	8.33 (2640)	6.39 (2530)	9.06 (2870)	8.67 (2750)	4.3 (7.7)	2.8 (5.1)	4.6 (8.2)	3.3 (5.9)
JP-8	9	13.40 (4250)	16.20 (5135)	15.60 (4950)	19.80 (6280)	2.2 (4.0)	3.3 (6.0)	2.7 (4.8)	9.9 (17.8)
JP-8	JP-8 Average[2]	8.49 (2690)	17.1 (5420)	11.9 (3770)	23.3 (7390)	1.8 (3.2)	2.6 (4.6)	5.6 (10.0)	4.7 (8.5)
JP-8	JP-8 Std. Dev.	2.89 (916)	8.74 (2770)	5.23 (1660)	12.6 (3990)	1.6 (2.8)	4.4 (7.9)	9.6 (17.2)	5.6 (10.1)
HRJ/JP-8	10	No data							
HRJ/JP-8	11	9.18 (2910)	7.55 (2390)	10.3 (3270)	12.60 (3990)	0.4 (0.7)	1.2 (2.2)	0.6 (1.1)	1.8 (2.7)
HRJ/JP-8	12	9.6 (3040)	8.92 (2830)	15.00 (4760)	12.50 (3960)	-2.6 (-4.7)	1.4 (2.6)	-2.2 (-3.9)	1.9 (3.4)
HRJ/JP-8	13	9.47 (3000)	6.88 (2180)	12.30 (3900)	10.90 (3450)	5.1 (9.2)	-2.7 (-4.8)	6.5 (11.7)	-2.1 (-3.8)
HRJ/JP-8	14	9.97 (3160)	4.06 (1290)	11.50 (3640)	4.67 (1480)	-2.3 (-4.2)	-1.6 (-8.3)	-2.2 (-3.9)	-4.3 (-7.8)
HRJ/JP-8	15	14.9 (4720)	5.10 (1620)	18.80 (5960)	6.33 (2010)	0.9 (1.6)	1.3 (2.4)	1.0 (1.8)	1.8 (3.3)
HRJ/JP-8	HRJ/JP-8 Blend Average	10.6 (3360)	6.50 (2060)	13.6 (4310)	9.40 2980	2.8 (0.5)	-0.7 (-1.2)	.8 (1.4)	-0.2 (-0.4)
HRJ/JP-8	HRJ /JP-8 Blend Std. Dev.	2.41 (764)	1.94 (615)	3.39 (1070)	3.67 (1160)	3.1 (5.6)	2.8 (5.1)	3.6 (6.4)	2.8 (5.1)
t-test probability		0.18	0.05	0.49	0.07	0.37	0.22	0.23	0.13

[1] These data are not included in the JP-8 averages and standard deviations s below

[2] Averages for the JP-8 downwind location include tests 4-9 only.

The data was strongly influenced by wind deflecting the flames in the vicinity of the instruments. All tests were conducted with pretest wind speed less than 3.1 m/s (7 mi/h), however this was sufficient to deflect the flames near the instruments. During test 3, the firefighting stream deflected the flames to the downwind instruments, resulting in burning the instrument lead wires. These instruments were located 20 ft away from the ring. Subsequent to test 3, the downwind instruments were located 40 ft from the ring. Deflection of the flames was an irregular event, and was not consistent from one fire to the next, so there is considerable variation between the fires. Mean and standard deviation and t-test probability values indicated in Table 4 do not include tests 1-3 for downwind instruments.

In several cases, the temperature rise data was negative, that is, the measured temperature dropped during the fire. Review of the videos indicate that this drop in temperature was associated with the smoke shadow shading the instruments, and the cooling was a result of elimination of the sun's radiant heat on the thermocouples while the smoke was present.

A t-test [5] was conducted to determine if the radiant heat and temperature rise data from the JP-8 and HRJ/JP-8 blend were samples from the same data set. Options selected were unpaired data with unequal variance and two tails. The probability values range from .05 to .049, indicating that the JP-8 and HRJ/JP-8 blend data are from different data sets. The crosswind radiometers indicated that the HRJ/JP-8 blend provided greater radiant heating, while the downwind radiometers indicated that the JP-8 provided greater radiant heating. Previous tests on smaller fires in a controlled environment without wind showed similar heat flux for the two fuels [6].

Radiant heat flux values from liquid hydrocarbon fires can be estimated by a method developed by Shorkri and Beyler [7],

$$\boldsymbol{q'' = 15.4\left(\frac{L}{D}\right)^{-1.59}\ kW/m^2 \quad q = 4880\left(\frac{L}{D}\right)^{-1.59}\ Btu/hr/ft^2}$$

where *L* is the distance from the center of the fire and *D* is the diameter of the circular pool fire. The formula calculates values at a height the same as the base of the fire and doesn't take into account flame height, however the radiometers were located approximately 0.9 m (3 ft) above the base of the fire, which is insignificant compared to the height of the flames. Using this formula, radiation for the downwind sensor was calculated to be 15.4 kW/m^2 and the crosswind sensor to be 24.3 kW/m^2. These calculated heat flux values are significantly higher than the average values measured, possibly due to wind blowing the flames away from the crosswind transducers.

The values from the JP-8 average and HRJ/JP-8 blend average in Table 4 are shown graphically (Figure 5 and Figure 6) with 95% confidence spans. The confidence spans represent the range of the average values if a very large number of tests were conducted. The very wide spans, particularly for the downwind data, reflect the large degree of variation between these tests. This variation was probably due to wind, which has a large effect on the position of the flames relative to the instruments. The effect of wind would probably be greater for the downwind instruments, since small breezes would provide greater variation in the direction of the wind.

The temperature rise data also shows significant overlap in the range of average values for the crosswind averages, but not for the maximum values. The magnitude of temperature rise overall is very small, and most of the spans of average values cross zero degrees rise. This indicates that the air near the fire is not heated as a result of the fire.

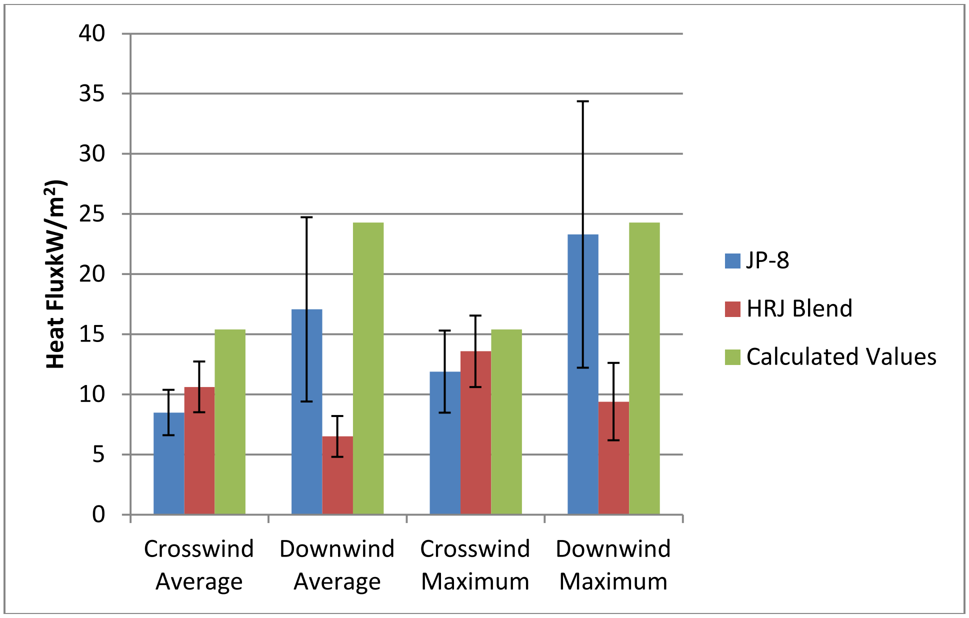

Figure 5. Average Heat Flux Values with 95% Confidence Span

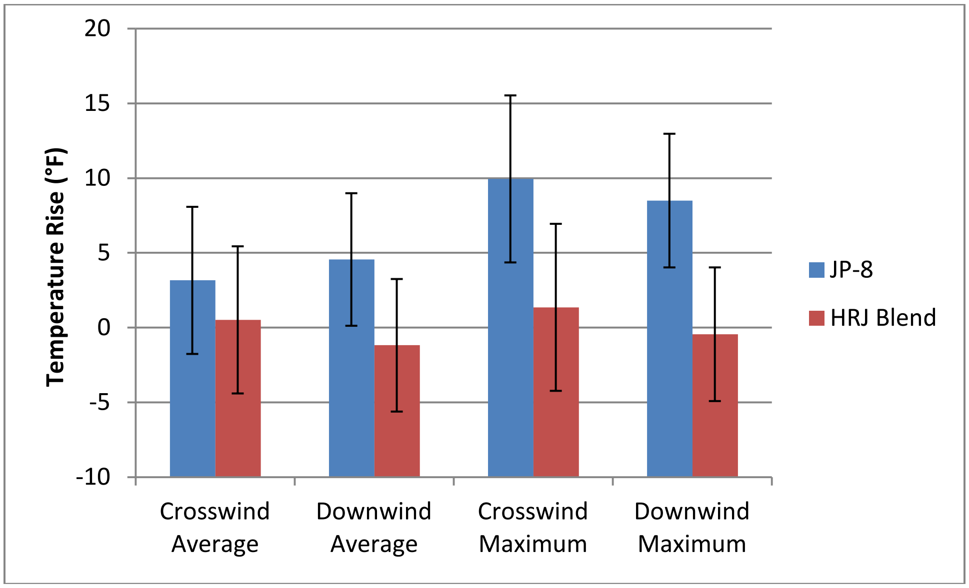

Figure 6. Average Temperature Rise with 95% Confidence Span

5. CONCLUSIONS AND RECOMMENDATIONS

- The HRJ/JP-8 blend fuel was extinguished effectively using AFFF with standard pressure and UHP.
- Large scale fire suppression results mirrored small scale results: AFFF is equally effective on JP-8 and HRJ/JP-8 blend fuel.
- Radiant heat flux measurements were inconclusive due to wind effects.

In conclusion, based on the results of these tests, modifications to the firefighting equipment and solutions are not required for extinguishment of fires involving a 50% blend of JP-8 and HRJ fuel for either standard pressure or UHP.

6. REFERENCES

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8. Gritzo, Louis A, Boucheron, Edwrd A, Murray, Doug, Fuel Temperature Distribution and Burning Rate in Large Pool Fires, Proposed for presentation at the Annual Conference on Fire Research, Gaithersburg MD,October 28-31,1996.(http://fire.nist.gov/bfrlpubs/fire96/PDF/f96098.pdf)

Appendix A: Calibrations

Table A-1. Water Tank

Water Height (in)	Water Removed (lb)	Water Removed (gal)	Tank Quantity (gal)	Water Temperature	Water Height (in)	Tank Quantity (gal)
32.25	200	24.03	1000.00	23	32.25	1000.0
31.5	200	24.03	975.97	23	31.50	976.0
30.75	200	24.03	951.93	23	30.75	951.9
29.9375	200	24.03	927.90	23	29.94	927.9
29.125	200	24.03	903.86	23	29.13	903.9
28.25	200	24.03	879.83	23	28.25	879.8
27.4375	200	24.03	855.79	23	27.44	855.8
26.625	200	24.03	831.76	23	26.63	831.8
25.8125	200	24.03	807.72	23	25.81	807.7
25	200	24.03	783.69	23	25.00	783.7
24.1875	200	24.03	759.65	23	24.19	759.7
23.375	200	24.03	735.62	21	23.38	735.6
22.5625	200	24.03	711.58	21	22.56	711.6
21.75	200	24.03	687.55	21	21.75	687.5
21	200	24.03	663.51	21	21.00	663.5
20.1875	200	24.03	639.48	21	20.19	639.5
19.3125	200	24.03	615.44	21	19.31	615.4
18.5	200	24.03	591.41	21	18.50	591.4
17.6875	200	24.03	567.37	21	17.69	567.4
16.875	200	24.03	543.34	21	16.88	543.3
16.125	200	24.03	519.30	21	16.13	519.3
15.25	200	24.03	495.27	21	15.25	495.3
14.4375	200	24.03	471.23	21	14.44	471.2
13.625	200	24.03	447.20	21	13.63	447.2
12.75	200	24.03	423.16	21	12.75	423.2
11.9375	200	24.03	399.13	21	11.94	399.1

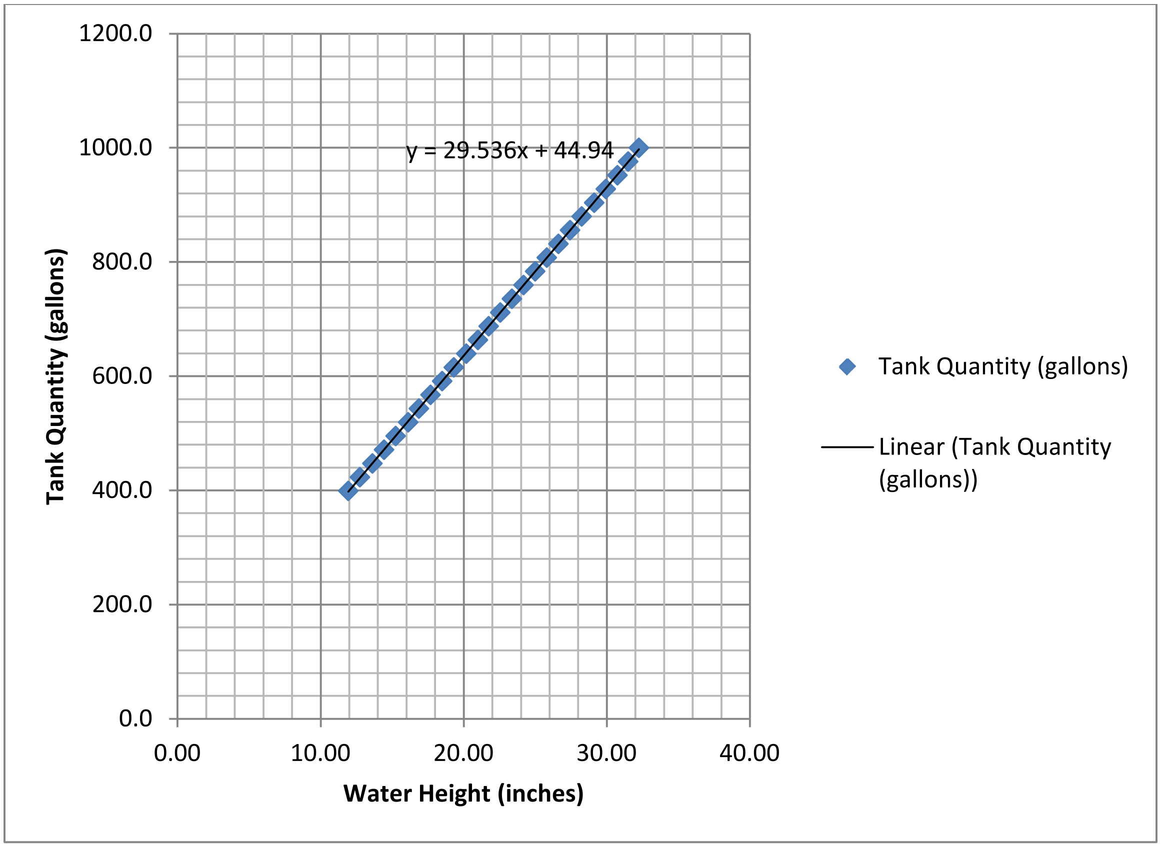

Figure A-1. Tank Calibration

Received for recalibration: 1/19/11 PAGE 1 OF 1 HF17026_B.DOC

CERTIFICATE OF CALIBRATION

DATE 2/10/11
CUSTOMER Applied Res. Assoc. Tyndall AFB, FL
P.O. NO. ESD11S0343
CERTIFICATE NO. 17027-1
MODEL NO. 64-25-20

SERIAL NO. 151471
SENSOR TYPE Gardon Gage
ABSORPTANCE 0.92
WINDOW None
REFERENCE STANDARD 120823
CALIBRATED BY 13
CALIBRATION RESULTS SUMMARY:
FULL SCALE OUTPUT LEVEL:
11.76 mV at 25 Btu/(ft²·s)
RESPONSIVITY:
0.4704 mV per Btu/(ft²·s), or
the inverse: 2.126 Btu/(ft²·s) per mV
Water: 10.8 °C 12 mL/s

UNLESS NOTED, CALIBRATION CONDITIONS:
Non-condensing Ambient Air at 23 ±3 °C
Relative Humidity Less Than 70%
Expanded uncertainty ±3% of responsivity.
Coverage factor k=2, ~95% confidence level.
Test uncertainty ratio (TUR) is less than 4:1.

Calibration was performed in compliance with ISO/IEC 17025, ANSI/NCSL Z540-1 and MIL-STD-45662A to MEDTHERM PI-20 with traceability to the National Institute of Standards and Technology.

This certificate applies only to the item described above. It is not to be reproduced, except in its entirety, without written permission from MEDTHERM Corporation.

ATTEST: Larry Jones
QA Manager ✓ President

MEDTHERM CORPORATION

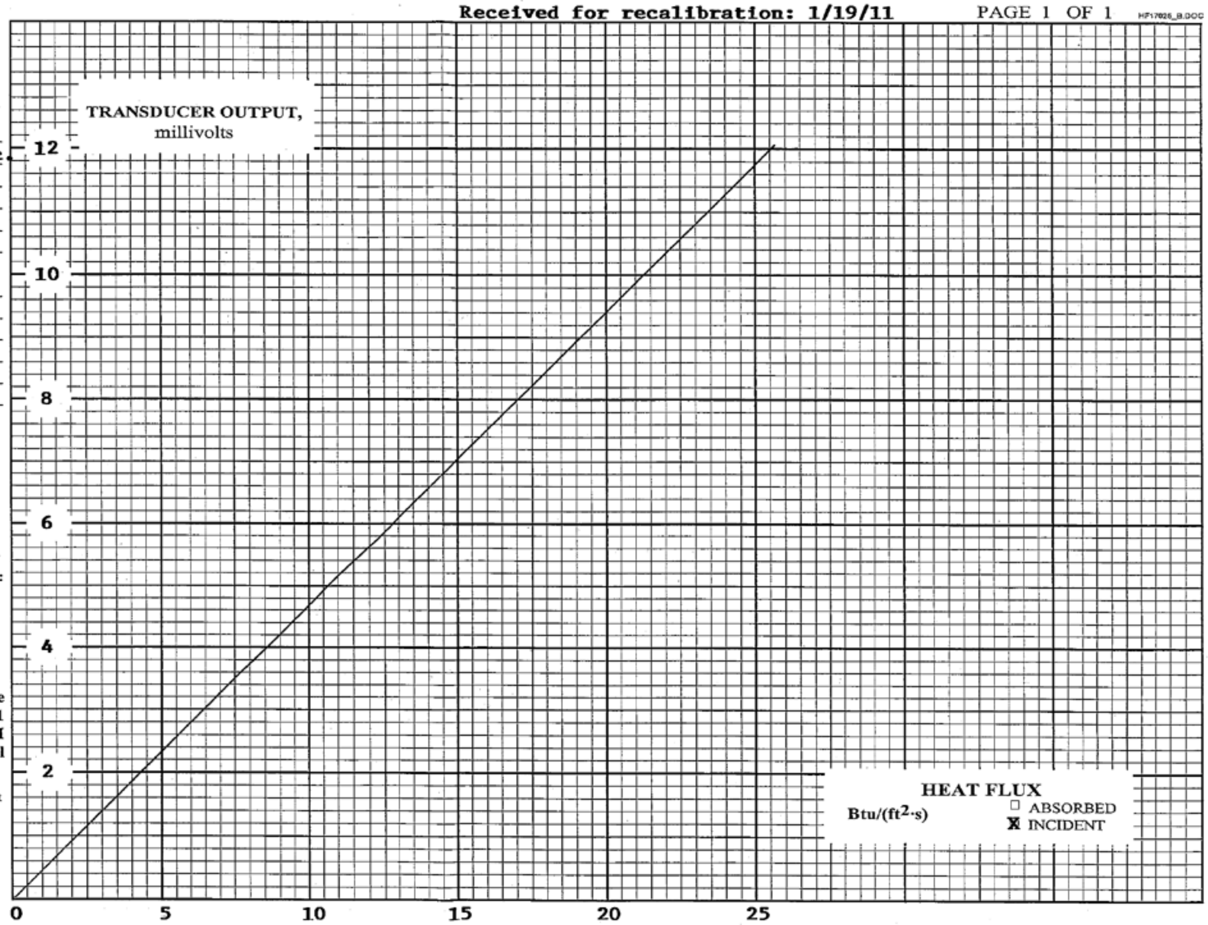

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Figure A-2. Radiometer Certificate of Calibration

Received for recalibration: 1/19/11 PAGE 1 OF 1 HF17005_B.DOC

CERTIFICATE OF CALIBRATION

DATE 2/10/11
CUSTOMER Applied Res. Assoc
Tyndall AFB, FL
P.O. NO. ESD11S0343
CERTIFICATE NO. 17027-2
MODEL NO. 64-25-20

SERIAL NO. 151472
SENSOR TYPE Gardon Gage
ABSORPTANCE 0.92
WINDOW None
REFERENCE STANDARD 120823
CALIBRATED BY 13

CALIBRATION RESULTS SUMMARY:
FULL SCALE OUTPUT LEVEL:
11.80 mV at 25 Btu/(ft^2·s)
RESPONSIVITY:
0.4720 mV per Btu/(ft^2·s), or
the inverse: 2.119 Btu/(ft^2·s) per mV
Water: 10.8 °C 12 mL/s

UNLESS NOTED, CALIBRATION CONDITIONS:
Non-condensing Ambient Air at 23 ±3 °C
Relative Humidity Less Than 70%
Expanded uncertainty ±3% of responsivity.
Coverage factor k=2, ~95% confidence level.
Test uncertainty ratio (TUR) is less than 4:1.

Calibration was performed in compliance with ISO/IEC 17025, ANSI/NCSL Z540-1 and MIL-STD-45662A to MEDTHERM PI-20 with traceability to the National Institute of Standards and Technology.

This certificate applies only to the item described above. It is not to be reproduced, except in its entirety, without written permission from MEDTHERM Corporation.

ATTEST:

____ QA Manager ✓ President

MEDTHERM CORPORATION

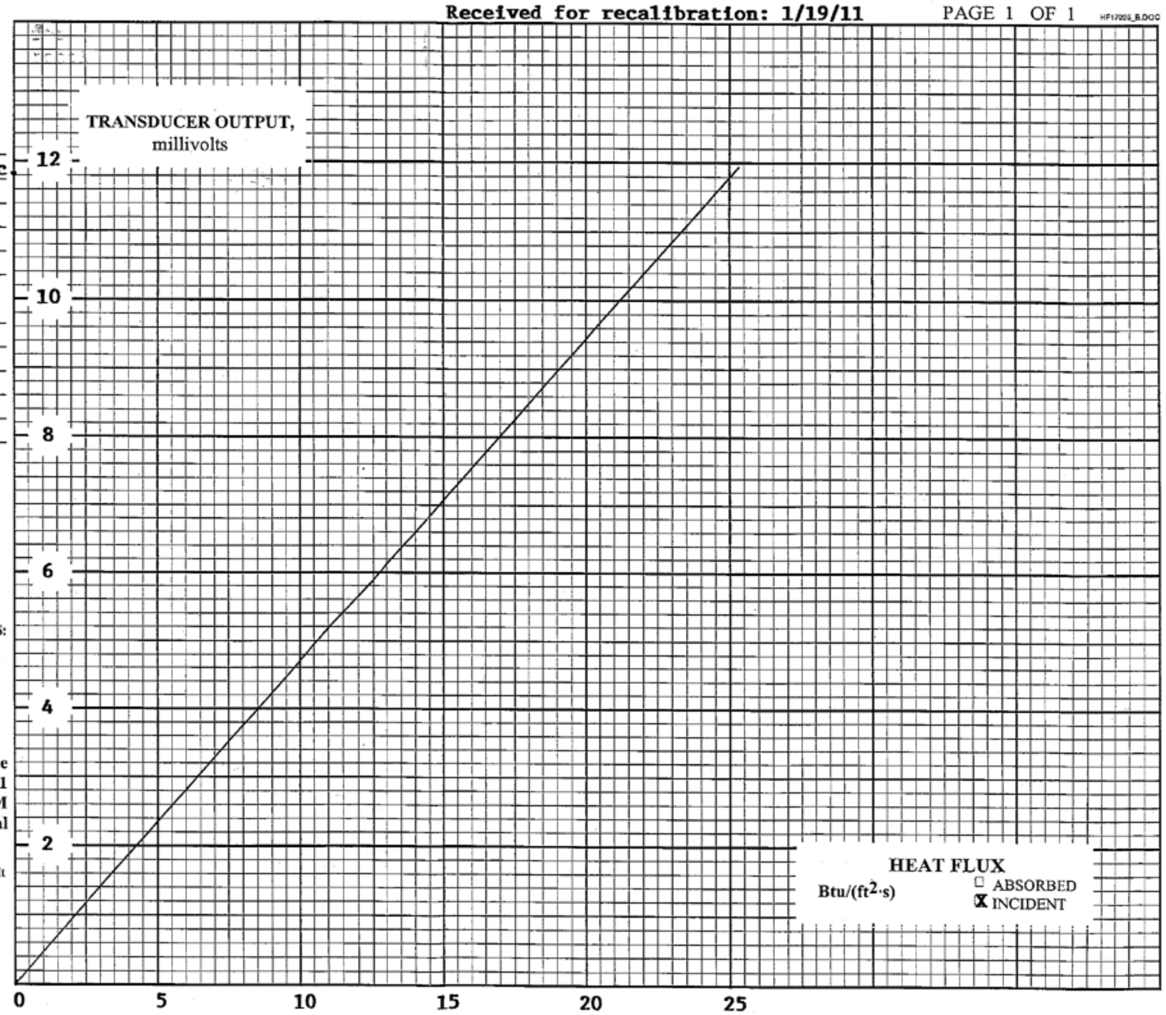

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Figure A-3. Radiometer Certificate of Calibration

Appendix B: Ring Area Measurements

The fire area was measured by obtaining the length of the sides of three separate inscribed triangles within the steel ring. Nine notches were filed into the top of the steel ring, defining the vertices of the triangles. The lengths of the sides were measured prior to each fire. The area of the ring (A) was determined by:

$$s = \frac{a+b+c}{2}$$

$$h = \sqrt{s(s-a)(s-b)(s-c)}$$

$$r = \frac{abc}{4h}$$

$$A = \pi r^2$$

Where a, b and c are the lengths of the triangle sides. The three values of area (*A*) were averaged for each fire. The variables S and H are intermediate values used to simplify the computation and does not represent any significant geometric property.

Table B-1. Triangle A

Test Number	a (ft)	b (ft)	c (ft)	S_a(ft)	R_a(ft)	A_a(ft^2)
1	67.00	67.75	68.75	101.75	39.17	4820
2	67.75	67.17	68.50	101.71	39.15	4816
3	71.00	69.92	70.42	105.67	40.67	5197
4	68.00	68.17	67.75	101.96	39.24	4838
5	68.58	68.50	68.42	102.75	39.55	4914
6	69.58	69.83	69.67	104.54	40.24	5087
7	70.21	69.75	69.83	104.90	40.37	5121
8	70.25	67.92	67.67	102.92	39.63	4934
9	68.25	70.17	68.67	103.54	39.86	4992
10	68.83	70.25	70.25	104.67	40.29	5100
11	71.00	68.67	69.83	104.75	40.33	5110
12	69.58	68.17	68.50	103.13	39.70	4951
13	69.33	68.33	68.33	103.00	39.65	4938
14	68.75	70.17	68.42	103.67	39.91	5004
15	69.00	69.33	69.83	104.08	40.06	5042

Table B-2. Triangle B

Test Number	a (ft)	b (ft)	c (ft)	S_b(ft)	R_b(ft)	A_b(ft^2)
1	70.17	68.83	67.67	103.33	39.79	4973
2	70.58	69.33	70.75	105.33	40.55	5165
3	68.33	68.25	67.67	102.13	39.31	4854
4	71.75	71.67	69.75	106.58	41.03	5290
5	71.50	71.42	70.17	106.54	41.01	5284
6	69.42	68.33	68.75	103.25	39.74	4962
7	68.50	69.67	69.50	103.83	39.97	5019
8	69.67	70.08	70.33	105.04	40.43	5136
9	68.33	69.67	68.58	103.29	39.76	4967
10	69.42	69.83	68.33	103.79	39.95	5015
11	68.83	68.50	69.83	103.58	39.87	4995
12	69.17	70.50	69.67	104.67	40.29	5100
13	69.50	70.83	69.25	104.79	40.34	5112
14	69.50	70.25	69.42	104.58	40.26	5091
15	50.58	69.58	69.75	94.96	37.38	4391

Table B-3. Triangle C

Test Number	a (ft)	b (ft)	c (ft)	S_c(ft)	R_c(ft)	A_c (ft^2)
1						
2	70.00	71.00	71.67	106.33	40.93	5264
3	70.92	69.58	70.83	105.67	40.68	5198
4	69.75	70.75	69.67	105.08	40.45	5140
5	70.67	69.50	69.25	104.71	40.31	5104
6	70.42	69.33	69.58	104.67	40.29	5099
7	70.54	69.88	69.50	104.96	40.40	5128
8	71.00	69.08	70.42	105.25	40.52	5158
9	71.00	70.58	68.33	104.96	40.41	5131
10	70.25	71.08	69.58	105.46	40.60	5177
11	69.83	69.83	69.75	104.71	40.30	5103
12	69.83	69.83	69.67	104.67	40.29	5099
13	69.67	69.75	69.83	104.63	40.27	5095
14	69.42	69.83	69.67	104.46	40.21	5079
15	69.67	69.67	69.33	104.33	40.16	5066

Appendix C: Labview Screens

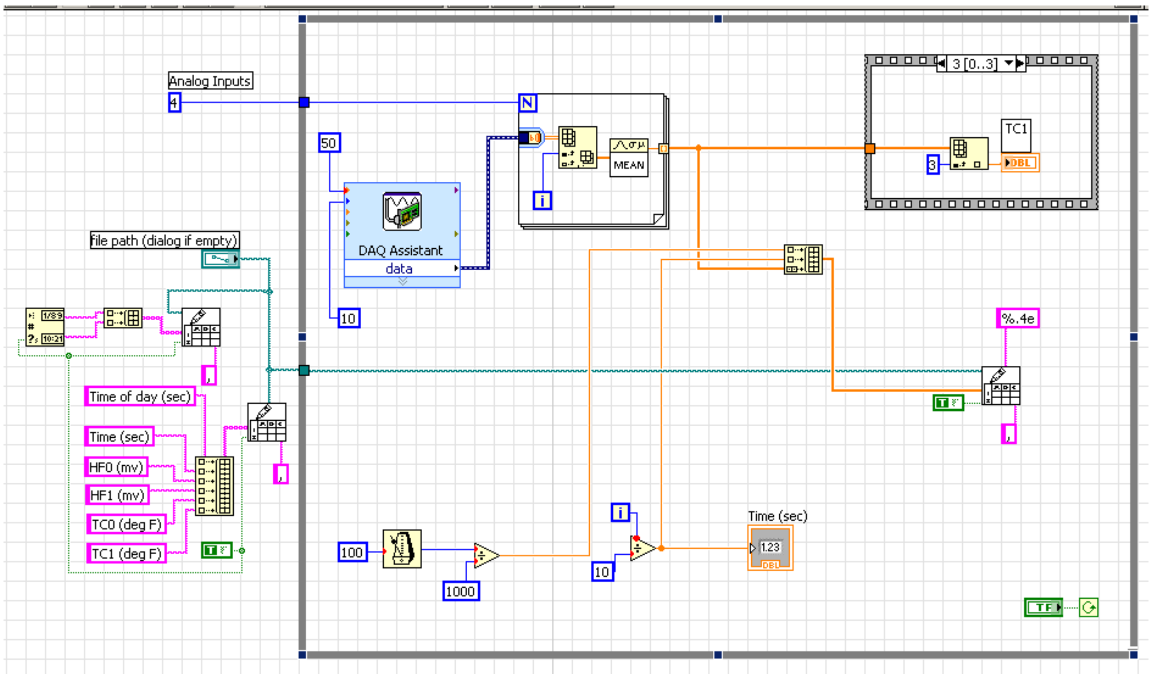

Figure C-1. Labview Diagram

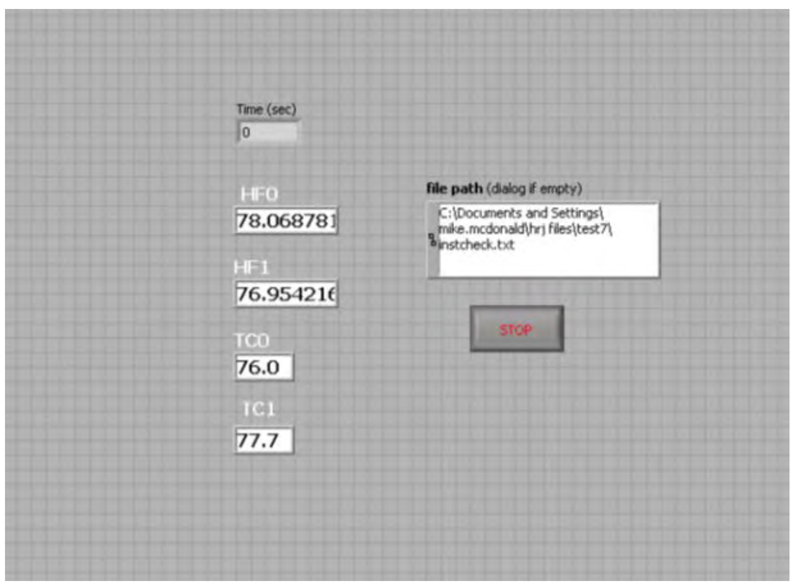

Figure C-2. Labview Front Screen

Appendix D: Uncertainty Estimates

Pit area: Uncertainty of the pit area was estimated as two standard deviations, which corresponds to a 95.45% confidence. The average computed pit area was 490 m^2, and the standard deviation of the pit area was 10.7 m^2. Consequently, the pit area uncertainty is

$$Area\ Uncertainty = \frac{2 * 10.7}{470} * 100 = 5\%$$

Agent Quantity: Agent quantity was calculated by:

$$\boldsymbol{Q(L) = \frac{(8.05*(H2-H1)*t)}{t2}} \qquad \boldsymbol{Q(gal) = \frac{29.54*(H2-H1)*t}{t2}}$$

This is the product of a constant, the difference between two height measurements, and two time measurements. From Appendix E, the average values of the height measurements are 645 mm (25.4 in) at the start and 508 mm (20.0 in) at the end, or 577 mm (22.7 in) overall. These measurements were obtained using a tape measure fixed to the manometer. The tape measure had 1.6 mm (1/16 in) increments, which could be read to 0.8 mm (1/32 in). Consequently, the water height difference uncertainty can be estimated by [D-1]:

$$Height\ uncertainty(H2 - H1) = \frac{\sqrt{.8^2 + .8^2}}{645 - 508} = 2.1\%$$ [D-1]

The time measurement uncertainty was estimated at 1 s. The average pumping time was 35 s, and the average extinguishment time was 26.5 s. Consequently, the uncertainties of these measurements are:

$$pumping\ time\ uncertainty = \frac{1}{35} = 2.9\%$$

$$extinguishment\ time\ uncertainty = \frac{1}{26.5} = 3.8\%$$

The overall uncertainty of agent quantity is:

$$Agent\ quantity\ uncertainty = \sqrt{.021^2 + .029^2 + .038^2} = 5.2\%$$ [D-1]

Agent Application Rate

Agent application rate is defined as Agent quantity divided by fire area, so

$$Agent\ application\ rate\ uncertainty = \sqrt{.05^2 + .052^2} = 7.2\%$$

[D-1] Taylor, John R, An Introduction to Error Analysis, ISBN 0-935702-75-X, 1997, page 78.

Appendix E: Extinguishment Data

	Mean A	Stdev A	Extinguishment Time	Pumping Time	H Start	H End	Agent Pumped	Flow Rate	Agent for Extinguishment	Application Rate	Wind Speed
Test Number	ft^2	ft^2	s	s	in	in	gal	gal/min	gal	gal/ft^2	mi/h
1	4897	108.1	32	61	29.94	21.38	252.9	248.8	132.7	0.0271	1.5
2	5082	235.6	20	20	30.81	28.13	79.4	238.1	79.4	0.0156	3.0
3	5083	198.1	33	34	27.38	21.88	162.4	286.7	157.7	0.0310	5.0
4	5089	229.9	39	46	21.88	15.19	197.5	257.6	167.5	0.0329	2.0
5	5101	185.3	34	45	29.19	21.94	214.1	285.5	161.8	0.0317	3.0
6	5049	75.7	24	29	21.88	17.00	144.0	297.9	119.2	0.0236	5.0
7	5089	61.2	32	35	26.69	20.91	170.8	292.7	156.1	0.0307	3.1
8	5076	123.2	21	39	30.75	25.25	162.4	249.9	87.5	0.0172	2.0
9	5030	88.7	19	27	24.50	20.50	118.1	262.5	83.1	0.0165	3.1
10	5097	81.2	21	29	20.50	16.44	120.0	248.3	86.9	0.0170	3.0
11	5069	64.5	30	37	30.38	24.72	167.1	270.9	135.5	0.0267	4.5
12	5050	85.7	26	34	24.00	18.38	166.1	293.2	127.0	0.0252	3.2
13	5048	95.8	18	27	17.19	13.31	114.5	254.3	76.3	0.0151	7.0
14	5058	47.3	26	34	25.44	20.25	153.2	270.4	117.2	0.0232	2.4
15	4833	383.5	22	28	19.63	15.44	123.7	265.0	97.2	0.0201	0.8

LIST OF SYMBOLS, ABBREVIATIONS, AND ACRONYMS

AFFF	aqueous film forming foam
AFRL	Air Force Research Laboratory
ASC/WNN	Aeronautical Systems Center Alternative Fuels Certification Division
BTUs/ft^2	British Thermal Unit per square foot; feet
BTUs/hr/ft^2	British Thermal Unit per hour per square foot; feet
°C	degrees Celsius
CAF	compressed air foam
°F	degrees Fahrenheit
ft	foot; feet
ft^2	square foot; feet
gal	gallon(s)
gal/in	gallons per inch
gal/min	gallons per minute
gal/ft^2	gallons per square foot; feet
in	inch(es)
h	hour(s)
HEFA	hydroprocessed esters and fatty acids fuel
HRJ	hydroprocessed renewable jet fuel
JP-8	jet propellant 8
Kg	kilograms
kPa	kilopascals
kW/m^2	kilowatts per square meterL liter(s)
Lb	pounds
L/s	liters per second
L/m^2	liters per square meter
L/mm	liters per millimeter
L/min	liters per minute
m	meter(s)
mi	mile(s)
mi/h	mile(s) per hour
min	minute(s)
mm	millimeter(s)
MPa	megapascals
psi	pounds per square inch
NFPA	National Fire Protection Association
s	second(s)
SE&V	support equipment and vehicles
STDEV	standard deviation
UHP	ultra high pressure
USAF	United States Air Force